4

The Dangerous Steam Engine

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4.1 Safety Devices

In large parts of our modern world, electric power is produced by heating water to produce steam, which is then fed to a steam turbine driving a generator. Every such energy plant contains a pressure vessel – a boiler.

Uncontrolled heating may raise the steam pressure to a level high enough to cause the boiler to burst, and this may result in great damage to people and plant. Such explosions were not uncommon in the early years of high-pressure steam technology.

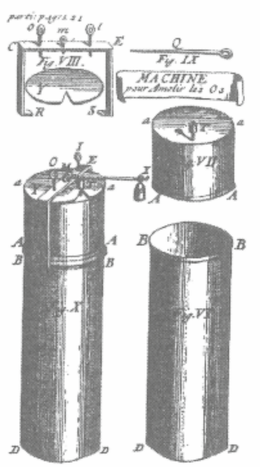

Figure 4.1. Papin's safety valve. Source: Höjer (1910)

A safety valve, first conceived by the Frenchman Denis Papin, found early use as a standard device to limit the steam pressure (Figure 4.1). By adjusting the position of the weight on the lever, the pressure was kept below a chosen limit. If it rose above that level, the valve opened and let out steam, thus reducing the

pressure. Three additional safety devices were later taken into use, permitting continuous observation of water level, steam pressure, and temperature.

The water level could be read directly on a vertical glass tube connected to the boiler (Figure 4.2). A "steam gauge," or manometer (Figure 4.3), showed the pressure, and the temperature could be read on a thermometer. As an ultimate means to prevent excessive heating, a safety fuse was sometimes mounted at the bottom of the boiler (Figure 4.4). A central hole in the plug was sealed by a metal alloy with a low melting temperature. If the temperature rose above that point, the seal melted and the plug opened, letting water and steam out of the boiler into the hearth to quench the fire.

Before these devices had found common use, knowledge about the state of the boiler was often meager, and the risk of a blow-up could be felt as a menace.

The most serious accidents occurred in steamships, where many unprotected people were often gathered in the vicinity of the engine room. Steamships had their first breakthroughs in coastal transport and on lakes, rivers, and canals. In those cases, there was no need for the ship to transport large amounts of coal and water on board, since bunkering could take place at various depots along the route as soon as the need arose. Long before trans-ocean steamship traffic had started, regular steamship routes had been established – an important innovation in commerce.

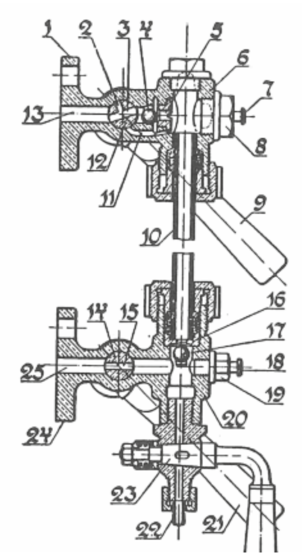

Figure 4.2. Device to monitor the water level. Source: Höjer (1910)

Examples of general references treating the issues that are discussed in this chapter are: Gordon (1978), Hammond (1956), Petroski (1985 and 1994), and Scanning (1976). More specific references to works dealing with pressure vessels can, for example, be found in: Bednar (1981), Gill (1970), Nichols (1979–83 and 1980), Spence and Tooth (1980), and Steele and Stahlkopf (1980).

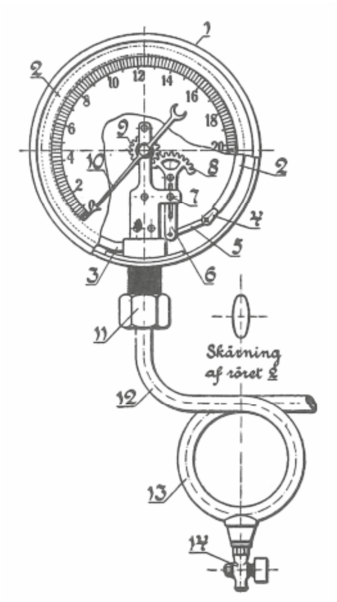

Figure 4.3. Manometer, to measure the steam pressure. Source: Höjer (1910)

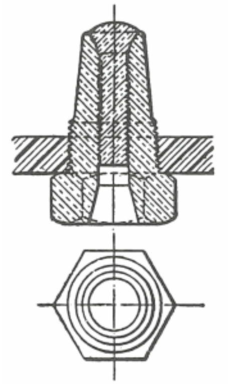

Figure 4.4. Safety fuse. Source: Höjer (1910)

4.2 Early Accidents in the Home Country of the Steam Engine

The cheapest and most comfortable way of traveling from London to Newcastle or to Edinburgh or Aberdeen in the 1820s was by steamboat. But the risks involved were not negligible. Between 1817 and 1839, 23 boiler blow-ups were registered in British steamships. After a much publicized accident in 1838, a parliamentary

commission was created, which submitted its report after a year. Public safety had become a concern for the expanding technological society.

The British Institution of Mechanical Engineers (IMechE) was created in Birmingham in 1847. An occupation, which had until then been looked upon as just a trade, had begun to gain a prestige on a par with that of the builders of canals, roads, and bridges, the Civil Engineers. Thirty years later, the Mechanicals moved to London, where their headquarters are still located, adjacent to those of the Civils just off Parliament Square.

An urgent task for the Mechanicals was to come to grips with problems of bursting steam boilers, but the reasons for such disasters often evaded the investigators. One inexplicable boiler blow-up was finally – after much deliberation – attributed to an assumed decomposition of water into hydrogen and oxygen, which then ignited! The ignorance was formidable, and boiler problems continued to cause worries for a long time. A report submitted to the IMechE in 1866 presented an account of 1046 blow-ups, which had caused a total of 4076 deaths.

IMechE then decided to attack the problems – unprejudiced and on a broad front. A statistical survey showed that 43 % of the failures were due to erroneous design or less professional repair work, whereas 28 % could have been warded off during a prescribed inspection. About 25 % were due to outright mismanagement, and 4 % were attributed to external circumstances, impracticable to control.

This survey resulted in a proposal for the compulsory regular inspection of steam boilers and for requirements that every boiler should be equipped with dual safety valves, and dual water-level gauges, in addition to a steam gauge. A national British pressure vessel code had begun to be created.

4.3 Simultaneous Development in the USA

By means of large flat-bottomed paddle steamers, the Mississippi had become an important transport route for both goods and passengers. Lucrative business possibilities opened up for owners of rapid steamships, and several ways were tried out to enhance the ships' performance, e.g., by placing a heavier counterweight on the safety-valve lever. Contests between paddle steamers, such as the one between Natchez and Eclipse (Figure 4.5) created excitement, but disaster was lurking, when the engines were taxed to the extreme.

Several events with bursting boilers on American river steamers in the early nineteenth century caused severe damage. Many passengers were killed, and cries for restrictions began to be heard, but the Constitution of the United States provided no legal means to act in such matters.

Between 1818 and 1824, the number of people killed by bursting steamship boilers rose to a total of 47 due to 15 blow-ups. When yet another such disaster occurred 1824 in New York harbor, killing 13 people, Congress finally acted and embarked upon a program to reduce the risks for the general public.

In that same year, the Franklin Institute was founded in Philadelphia, with the task to perform research into "the mechanical sciences." The scientific *Journal of the Franklin Institute*, from its start, devoted much attention to the aggravating

steam boiler problems. The need for legislation was discussed, but agreement could not be reached, so a committee was set up to investigate the reasons for recorded blow-ups and also to perform tests with boilers under increasing internal pressure.

In the meantime, boiler disasters continued at an appalling rate. From 1825 to 1830, a total of 42 explosions were recorded in the US, killing 273 persons. After "50 or 60 persons" had been killed by a disaster in 1830, onboard SS Helen McGregor near Memphis in Tennessee, the federal government finally yielded, and gave a substantial research grant to the Franklin Institute. This was the first occasion on which the US government gave financial support to an engineering research project.

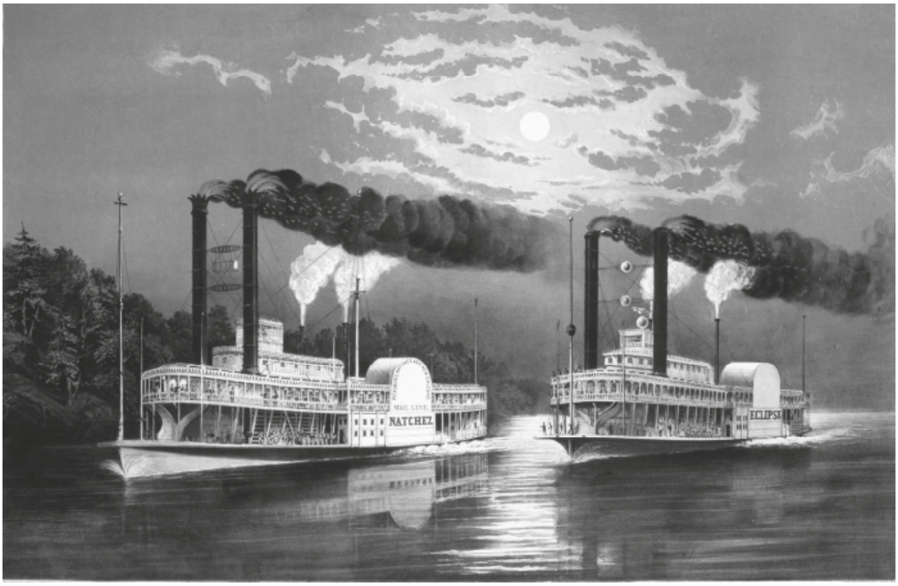

Figure 4.5. The race between Natchez and Eclipse in 1855. (Published with permission from Science Museum, London, UK)

The ensuing technical report recommended legislation prescribing compulsory boiler tests every third month, with a pressure up to three times the normal working pressure. But, again, the resistance against legislation was so strong that the report was rejected. Boiler explosions continued to occur for years ahead, on the Mississippi and other major rivers.

In 1880, The American Society of Mechanical Engineers (ASME) was founded, and steam boiler safety soon took an important place on its agenda. The ASME Boiler Codes, first published in 1911, have since become a very influential basis for the development of the safe design of all kinds of pressure vessels, in the US as well as in many other countries.

4.4 Nuclear Engineering – Steam Technology at the Crossroads

The steam age may be stated to have been born in 1712, when Thomas Newcomen's first pumping machine was erected at a coal mine near Dudley Castle in England (Figure 4.6). During the ensuing almost 300 years, the technology has passed through a series of stages, from atmospheric to high pressure, from a pumping machine to a producer of rotary motion, and from a stationary to a mobile energy transformer.

Common to all these incarnations is the boiler, where heating of water produces steam. Different heat sources have been used: wood, coal, oil, gas, or nuclear fuel.

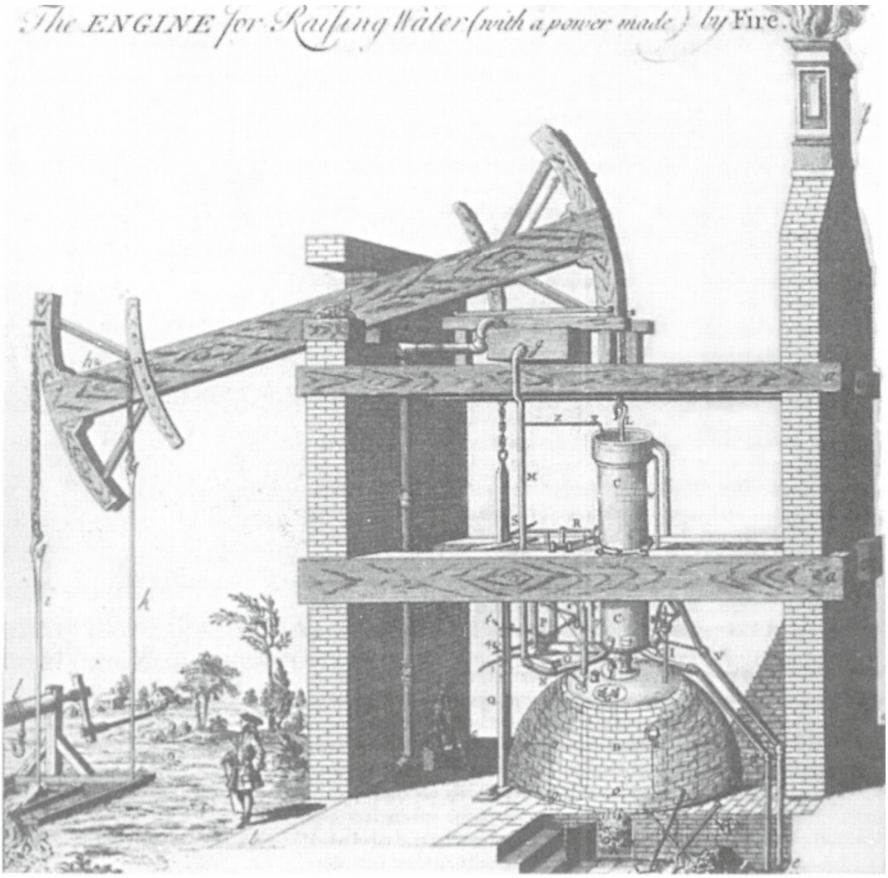

Figure 4.6. The oldest known illustration of Newcomen's pumping machine (1771). (Published with permission from Worcester College, Oxford, UK)

In the early stages of the steam age – as shown earlier – the uncontrolled rise of the steam pressure was an ever present menace. In addition, corrosion (rust) in the boiler walls created a hazard, growing with the age of the boiler. A manhole

became a compulsory requirement for every boiler, making regular inspection of its inside possible.

Taken together, all such safety arrangements – with firm regulations both as to handling and as to inspection intervals – have resulted in a technology where the risks of boiler blow-ups have become negligibly small.

In addition, theoretical analyses of stresses and strains in pressure vessels have been developed to include the effects of various small deviations from the intended design.

The types of damage caused by bursting boilers during the first centuries of the steam age are not experienced as serious threats anymore – with one exception, namely boilers in nuclear power stations. Here, a blow-up of a main pressure vessel would probably mean the end of nuclear engineering as we know it today. The state of the boiler itself is, therefore, always analyzed with particular respect to the deterioration of the boiler material, due to long-term irradiation. In addition, material samples which have been immersed in the boiler ever since the plant became operative are examined during annual closure periods.

Special attention has also been given to the consequences of certain other events, such as bearings in machinery running hot, or suddenly excited vibrations, both of which might require an emergency stop of the entire plant. An extremely dangerous situation, termed "LOCA" (loss of coolant accident in nuclear engineering parlance), could cause a meltdown in the reactor hearth, in the event that all safety systems became inactive at the same time. For several reasons, such a situation is, however, extremely unlikely:

- Pressure vessels and pipelines in nuclear power stations are designed by the same experts who have successfully designed safe boilers as well as pipework for conventional power stations.
- Before a nuclear power station is commissioned to operate, rigorous inspection programs with the testing of controls are carried out.
- These tests are repeated at regular predetermined intervals, throughout the lifetime of the plant.

Reactor safety studies have also included hypothetical events such as a sudden rupture of the main steam pipe from the reactor to the turbine, causing steam under high pressure to gush out. The reactive force exerted on the reactor vessel would cause severe damage to the plant, but all previous experience indicates that such a situation is extremely unlikely.

Nuclear power stations are normally not located in earthquake-prone regions. Disaster could of course be inflicted upon a nuclear power plant due to sabotage or acts of war, but such kinds of risk will not be further discussed here.

In conclusion, lengthy experience of severe disasters in steam technology has come to foster a deep sense of societal responsibility among engineers and management. Few branches of engineering are as strictly ruled by codes and regulations.

4.5 Other Examples of Historical Safety Measures

4.5.1 Dramatic Accidents and Slowly Acting Dangers

Dangerous events occur in many walks of life, events which have inspired important safety improvements. A few examples, not relating to high-pressure steam technology, will be shown next.

A fire in a department store in Boston, Massachusetts, in the late nineteenth century had frightful consequences. The main doors could open only inwards, and therefore a great number of visitors could not escape, and were burned to death. Since then, it is prohibited by US federal law to use such doors in buildings open to the general public.

Day-to-day safety improvements are continuously being carried through, often based on recordings from insurance companies. TV supervision in car tunnels, regular tests of alert systems, and flying inspections of car drivers have assisted in diminishing accidents in road traffic.

Dramatic disasters often dominate in discussions of risks in modern life, whereas slowly acting disturbances on humans in our technological society tend to be disregarded. The danger of high sound levels in industrial workplaces – or in music arenas – may often become manifest only after an extended time. Monotonous work at computer terminals may induce pain in muscles or joints. Long-term exposure to certain chemicals – even in a very diluted form – may eventually lead to detrimental effects.

Much effort and penetrating research have been devoted to minimizing risks in our technological society. I shall conclude this brief account with some examples of technical solutions to safety problems.

4.5.2 The Falun Mine

One of the main problems in deep underground mining has always been to keep the mine free from water penetrating from roofs and walls. The Newcomen machines, precursors of all later steam engines, were constructed for this purpose. If the pump failed, it was important to warn the miners so that they could climb the ladders and exit the mine in time.

The automatic warning system at Falun consisted of a small chiming bell, driven by a water wheel, which was in turn fed by water from the mine pumps. If the pumps failed, the chiming ended abruptly, signaling imminent danger.

This "reversed" system is an example of a totally reliable solution to the warning problem: Danger is indicated not by a sounding signal but by a sudden silence. Everyone then knows that the pumps must have stopped – or that the bell has got stuck. In any case – for safety's sake – it is best to get out immediately!

4.5.3 The Otis Elevator

When the first person elevators were installed in high-rise buildings – in particular in major cities in the United States – insistence on safety design was soon brought forward to prevent a disaster, should the rope break.

The designer of one elevator, Mr. Elisha Graves Otis (1811–61), created quite a sensation during a demonstration at the Crystal Palace Exhibition in New York 1854 (Figure 4.7). Ratchets had been installed on each side of the shaft, and pawls on the cage were held clear of the ratchets as long as the rope remained stretched. If the rope broke, springs would immediately force the pawls out to engage the ratchets – and stop the fall of the cage.

During the demonstration, Mr. Otis stood calmly in the open cage and, when an assistant used an axe to cut the rope, the cage fell a few inches before it halted – and the spectators applauded.

Figure 4.7. Elisha Graves Otis' demonstration in New York 1854. (Source: TAILPIECE. Elisha Otis. After Steelways 9, no. 5, back cover, 1953. American Iron and Steel Institute, New York. D.E. Wodall)

4.5.4 Sundry Safety Equipment

Safety equipment, simple or more advanced, may serve the protection of human health in traffic (seat belts, crash helmets, crash cushions), or at the work place

(protective eye glasses, ear plugs) and also the limiting of property damage (electric fuses, fire alarms).

Hospitals are vulnerable institutions, where a sudden power failure may have perilous consequences, e.g., in an operating theatre. An emergency system to protect vital systems may consist of the following: a heavy flywheel, driven by an electric motor, is kept in steady rotation. If a power failure occurs, the flywheel is immediately clutched to a diesel engine, which then starts and takes over to drive a replacement generator.

Modern industrial production often uses hydraulically operating machinery, e.g., presses for plate-forming in car manufacture. The operator places the work piece in the press, and must then use both hands to press two start buttons simultaneously, so as to avoid getting one of them crushed. The press cannot be started by pressing only one of the two buttons.

Already in their first generation, electric locomotives were equipped with a "dead man's handle," which automatically actuated the brake, should the driver release his hold. This type of safety arrangement is now commonly used in much other equipment, such as power lawnmowers.

The railways have always been highly safety minded for the protection of the passengers. Thus, the doors of a railway carriage *cannot* normally be opened when the train is moving.

In contrast to the small risks involved in train travel, automobile traffic – for obvious reasons – leaves the passengers less protected. It is a challenge for society to develop much safer conditions for travel on the highways.

4.6 Concluding Remarks

In our technological world, national characteristics have become less dominant than before. International cooperation relating to safety in modern societies has resulted in almost universally accepted rules and regulations.

Nearly three hundred years ago, the steam engine led the way in research into technological safety problems which required scientific study before they could be mastered. It has become a common interest between actors in this field to show openness, a hopeful development for the future.

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